Spectroscopy and Strong Decays of Charmed Baryons

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Spectroscopy and strong decays of the charmed baryons are reviewed. Possible spin-parity quantum numbers of several newly observed charmed baryon resonances are discussed. Strong decays of charmed baryons are analyzed in the framework of heavy hadron chiral perturbation theory in which heavy quark symmetry and chiral symmetry are synthesized.

1. Introduction

In the past years many new excited charmed baryon states have been discovered by BaBar, Belle and CLEO. In particular, B factories have provided a very rich source of charmed baryons both from B decays and from the continuum $e^+e^- \to c\bar{c}$. A new era for the charmed baryon spectroscopy is opened by the rich mass spectrum and the relatively narrow widths of the excited states. Experimentally and theoretically, it is important to identify the quantum numbers of these new states and understand their properties. Since the pseudoscalar mesons involved in the strong decays of charmed baryons are soft, the charmed baryon system offers an excellent ground for testing the ideas and predictions of heavy quark symmetry of the heavy quarks and chiral symmetry of the light quarks.

2. Spectroscopy

Charmed baryon spectroscopy provides an ideal place for studying the dynamics of the light quarks in the environment of a heavy quark. The charmed baryon of interest contains a charmed quark and two light quarks, which we will often refer to as a diquark. Each light quark is a triplet of the flavor SU(3). Since $\mathbf{3} \times \mathbf{3} = \bar{\mathbf{3}} + \mathbf{6}$, there are two different SU(3) multiplets of charmed baryons: a symmetric sextet $\mathbf{6}$ and an antisymmetric antitriplet $\bar{\mathbf{3}}$.

In the quark model, the orbital angular momentum of the light diquark can be decomposed into $\mathbf{L}_\ell = \mathbf{L}_\rho + \mathbf{L}_\lambda$. where $\mathbf{L}_\rho$ is the orbital angular momentum between the two light quarks and $\mathbf{L}_\lambda$ the orbital angular momentum between the diquark and the charmed quark. The lowest-lying orbitally excited baryon states are the p-wave charmed baryons. Denoting the quantum numbers L_ρ and L_λ as the eigenvalues of $\mathbf{L}_\rho^2$ and $\mathbf{L}_\lambda^2$, respectively, the p-wave heavy baryon can be either in the $(L_\rho = 0, L_\lambda = 1)$ λ-state or the $(L_\rho = 1, L_\lambda = 0)$ ρ-state. It is obvious that the orbital λ-state (ρ-state) is symmetric (antisymmetric) under the interchange of two light quarks q_1 and q_2. The total angular momentum of the diquark is $\mathbf{J}_\ell = \mathbf{S}_\ell + \mathbf{L}_\ell$ and the total angular momentum of the charmed baryon is $\mathbf{J} = \mathbf{S}_c + \mathbf{J}_\ell$. In the heavy quark limit, the spin of the charmed quark S_c and the total angular momentum of the two light quarks J_ℓ are separately conserved.

There are seven lowest-lying p-wave Λ_c arising from combining the charmed quark spin S_c with light constituents in $J_\ell^{P_\ell} = 1^-$ state: three $J^P = \frac{1}{2}^-$ states, three $J^P = \frac{3}{2}^-$ states and one $J^P = \frac{5}{2}^-$ state. They form three doublets $\Lambda_{c1}(\frac{1}{2}^-, \frac{3}{2}^-), \tilde{\Lambda}_{c1}(\frac{1}{2}^-, \frac{3}{2}^-), \tilde{\Lambda}_{c2}(\frac{3}{2}^-, \frac{5}{2}^-)$ and one singlet $\tilde{\Lambda}_{c0}(\frac{1}{2}^-)$ in the notation $\Lambda_{cJ_\ell}(J^P)$, where we have used a tilde to denote the multiplets antisymmetric in the orbital wave functions under the exchange of two light quarks. Quark models [1] indicate that the untilde states for Λ- and Σ-type charmed baryons with symmetric orbital wave functions lie about 150 MeV below the tilde ones. The two states in each doublet with $J = J_\ell \pm \frac{1}{2}$ are nearly degenerate; their masses split only by a chromomagnetic interaction.

The next orbitally excited states are the positive parity excitations with $L_\rho + L_\lambda = 2$. There are two multiplets for the first positive-parity excited Λ_c with the symmetric orbital wave function, corresponding to $L_\lambda = 2, L_\rho = 0, L = 2$ and $L_\lambda = 0, L_\rho = 2, L = 2$, see Table I (for other charmed baryons, see [2] for details). For the case of $L_\lambda = L_\rho = 1$, the total orbital angular momentum L_ℓ of the diquark is 2, 1 or 0. Since the orbital states are antisymmetric under the interchange of two light quarks, we shall use a tilde to denote the $L_\lambda = L_\rho = 1$ states. The Fermi-Dirac statistics for baryons yields seven more multiplets for positive-parity excited Λ_c states.

The observed mass spectra and decay widths of charmed baryons are summarized in Table II. For the experimental status of charmed baryons, see [3]. In the following we discuss some of the new excited charmed baryon states:

2.1. Λ_c

It is known that $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ form a doublet $\Lambda_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$ [4]. The dominant decay mode is $\Sigma_c\pi$ in an S wave for $\Lambda_{c1}(\frac{1}{2}^-)$ and $\Lambda_c\pi\pi$ in a P wave for $\Lambda_{c1}(\frac{3}{2}^-)$. (The two-body mode $\Sigma_c\pi$ is a D-wave in $\Lambda_c(\frac{3}{2}^-)$ decay.) This explains why the width

Table I The first positive-parity excitations of Λ charmed baryons and their quantum numbers. States with antisymmetric orbital wave functions (i.e. $L_\rho = L_\lambda = 1$) under the interchange of two light quarks are denoted by a tilde. There are two multiplets Λ_{c2} and $\hat{\Lambda}_{c2}$ with symmetric orbital wave functions arising from the orbital states $L_\rho = 0, L_\lambda = 2$ and $L_\rho = 2, L_\lambda = 0$, respectively. We use a hat to distinguish between them.

State	SU(3)$_F$	S_ℓ	L_ℓ	$J_\ell^{P_\ell}$
$\Lambda_{c2}(\frac{3}{2}^+, \frac{5}{2}^+)$	$\bar{\mathbf{3}}$	0	2	2^+
$\hat{\Lambda}_{c2}(\frac{3}{2}^+, \frac{5}{2}^+)$	$\bar{\mathbf{3}}$	0	2	2^+
$\tilde{\Lambda}_{c1}(\frac{1}{2}^+, \frac{3}{2}^+)$	$\bar{\mathbf{3}}$	1	0	1^+
$\tilde{\Lambda}'_{c0}(\frac{1}{2}^+)$	$\bar{\mathbf{3}}$	1	1	0^+
$\tilde{\Lambda}'_{c1}(\frac{1}{2}^+, \frac{3}{2}^+)$	$\bar{\mathbf{3}}$	1	1	1^+
$\tilde{\Lambda}'_{c2}(\frac{3}{2}^+, \frac{5}{2}^+)$	$\bar{\mathbf{3}}$	1	1	2^+
$\tilde{\Lambda}''_{c1}(\frac{1}{2}^+, \frac{3}{2}^+)$	$\bar{\mathbf{3}}$	1	2	1^+
$\tilde{\Lambda}''_{c2}(\frac{3}{2}^+, \frac{5}{2}^+)$	$\bar{\mathbf{3}}$	1	2	2^+
$\tilde{\Lambda}''_{c3}(\frac{5}{2}^+, \frac{7}{2}^+)$	$\bar{\mathbf{3}}$	1	2	3^+

of $\Lambda_c(2625)^+$ is narrower than that of $\Lambda_c(2595)^+$.

$\Lambda_c(2765)^+$ is a broad state ($\Gamma \approx 50$ MeV) first seen in $\Lambda_c^+\pi^+\pi^-$ by CLEO [5]. It appears to resonate through Σ_c and probably also Σ_c^*. However, whether it is a Λ_c^+ or a Σ_c^+ or whether the width might be due to overlapping states are not known. According to PDG [6], this state has a nickname, namely, $\Sigma_c(2765)^+$. The Skyrme model [7] and the quark model [1] suggest a $J^P = \frac{1}{2}^+$ Λ_c state with a mass 2742 and 2775 MeV, respectively. Therefore, $\Lambda_c(2765)^+$ could be a first positive-parity excitation of Λ_c. However, two recent studies based on the relativistic quark model advocate a different assignment: a radial excitation $2\frac{1}{2}^+$ by [8] and a negative-parity state with $J^P = \frac{5}{2}^-$ by [9].

The state $\Lambda_c(2880)^+$ first observed by CLEO [5] in $\Lambda_c^+\pi^+\pi^-$ was also seen by BaBar in the D^0p spectrum [10]. It was originally conjectured that, based on its narrow width, $\Lambda_c(2880)^+$ might be a $\tilde{\Lambda}_{c0}^+(\frac{1}{2}^-)$ state [5]. Recently, Belle has studied the experimental constraint on the J^P quantum numbers of $\Lambda_c(2880)^+$ [11]. The angular analysis of $\Lambda_c(2880)^+ \to \Sigma_c^{0,++}\pi^\pm$ indicates that $J = \frac{5}{2}$ is favored over $J = \frac{1}{2}$ or $\frac{3}{2}$. In the quark model, the candidates for the spin-$\frac{5}{2}$ state are $\Lambda_{c2}(\frac{5}{2}^+)$, $\hat{\Lambda}_{c2}(\frac{5}{2}^+)$, $\tilde{\Lambda}_{c2}(\frac{5}{2}^-)$, $\tilde{\Lambda}'_{c2}(\frac{5}{2}^+)$, $\tilde{\Lambda}''_{c2}(\frac{5}{2}^+)$ and $\tilde{\Lambda}''_{c3}(\frac{5}{2}^+)$ (see Table I). And only one of them has odd parity.

Belle has also studied the resonant structure of $\Lambda_c(2880)^+ \to \Lambda_c^+\pi^+\pi^-$ and found the existence of the $\Sigma_c^*\pi$ intermediate states [11]. The ratio of $\Sigma_c^*\pi/\Sigma\pi$ is measured to be

$$R \equiv \frac{\Gamma(\Lambda_c(2880) \to \Sigma_c^*\pi^\pm)}{\Gamma(\Lambda_c(2880) \to \Sigma_c\pi^\pm)} = (24.1 \pm 6.4^{+1.1}_{-4.5})\%. \quad (1)$$

For $J^P = \frac{5}{2}^-$, $\Lambda_c(2880)$ decays to $\Sigma_c^*\pi$ and $\Sigma_c\pi$ in a D wave and we obtain

$$\frac{\Gamma\left(\tilde{\Lambda}_{c2}(5/2^-) \to [\Sigma_c^*\pi]_D\right)}{\Gamma\left(\tilde{\Lambda}_{c2}(5/2^-) \to [\Sigma_c\pi]_D\right)} = \frac{7}{2}\frac{p_\pi^5(\Lambda_c(2880) \to \Sigma_c^*\pi)}{p_\pi^5(\Lambda_c(2880) \to \Sigma_c\pi)} = 1.45\,, \quad (2)$$

where the factor of 7/2 follows from heavy quark symmetry. Hence, the assignment of $J^P = \frac{5}{2}^-$ for $\Lambda_c(2880)$ is disfavored. For $J^P = \frac{5}{2}^+$, Λ_{c2}, $\hat{\Lambda}_{c2}$, $\tilde{\Lambda}'_{c2}$ and $\tilde{\Lambda}''_{c2}$ with $J_\ell = 2$ decay to $\Sigma_c\pi$ in a F wave and $\Sigma_c^*\pi$ in F and P waves. Neglecting the P-wave contribution for the moment,

$$\frac{\Gamma(\Lambda_{c2}(5/2^+) \to [\Sigma_c^*\pi]_F)}{\Gamma(\Lambda_{c2}(5/2^+) \to [\Sigma_c\pi]_F)} = \frac{4}{5}\frac{p_\pi^7(\Lambda_c(2880) \to \Sigma_c^*\pi)}{p_\pi^7(\Lambda_c(2880) \to \Sigma_c\pi)} = 0.23\,. \quad (3)$$

At first glance, it appears that this is in good agreement with experiment. However, the $\Sigma_c^*\pi$ channel is available via a P-wave and is enhanced by a factor of $1/p_\pi^4$ relative to the F-wave one. Unfortunately, we cannot apply heavy quark symmetry to calculate the contribution of the $[\Sigma_c^*\pi]_F$ channel to the ratio R as the reduced matrix elements are different for P-wave and F-wave modes. In this case, one has to reply on a phenomenological model to compute the ratio R. At any event, the $\Sigma_c^*\pi$ mode produced in $\Lambda_c(2880)$ is *a priori* not necessarily suppressed relative to $[\Sigma_c\pi]_F$. Therefore, if $\Lambda_c(2880)^+$ is one of the states Λ_{c2}, $\hat{\Lambda}_{c2}$, $\tilde{\Lambda}'_{c2}$ and $\tilde{\Lambda}''_{c2}$, the prediction $R = 0.23$ is not robust as it can be easily upset by the contribution from the P-wave $\Sigma_c^*\pi$.

As for $\tilde{\Lambda}''_{c3}(\frac{5}{2}^+)$, it decays to $\Sigma_c^*\pi$, $\Sigma_c\pi$ and $\Lambda_c\pi$ all in F waves. Since $J_\ell = 3, L_\ell = 2$, it turns out that

$$\frac{\Gamma(\Lambda''_{c3}(5/2^+) \to [\Sigma_c^*\pi]_F)}{\Gamma(\Lambda''_{c3}(5/2^+) \to [\Sigma_c\pi]_F)} = \frac{5}{4}\frac{p_\pi^7(\Lambda_c(2880) \to \Sigma_c^*\pi)}{p_\pi^7(\Lambda_c(2880) \to \Sigma_c\pi)} = 0.36\,. \quad (4)$$

Although this deviates from the experimental measurement (1) by 1σ, it is a robust prediction. This has motivated Chun-Khiang Chua and me to conjecture that that the first positive-parity excited charmed baryon $\Lambda_c(2880)^+$ could be an admixture of $\Lambda_{c2}(\frac{5}{2}^+)$, $\hat{\Lambda}_{c2}(\frac{5}{2}^+)$ and $\Lambda''_{c3}(\frac{5}{2}^+)$ [2].

It is worth mentioning that very recently the Peking group [12] has studied the strong decays of charmed baryons based on the so-called $^3P_0$ recombination model. For the $\Lambda_c(2880)$, Peking group found that (i) the possibility of $\Lambda_c(2880)$ being a radial excitation is ruled out as its decay into D^0p is prohibited in the $^3P_0$ model if $\Lambda_c(2880)$ is a first radial excitation of Λ_c, and (ii) the only possible assignment is $\Lambda''_{c3}(\frac{5}{2}^+)$

Table II Mass spectra and decay widths (in units of MeV) of charmed baryons taken from [2]. Except for the parity of the lightest Λ_c^+ and the spin-parity of $\Lambda_c(2880)^+$, none of the other J^P quantum numbers given in the table has been measured. One has to rely on the quark model to determine the spin-parity assignments.

State	J^P	S_ℓ	L_ℓ	$J_\ell^{P_\ell}$	Mass	Width	Principal decay modes
Λ_c^+	$\frac{1}{2}^+$	0	0	0^+	2286.46 ± 0.14		weak
$\Lambda_c(2595)^+$	$\frac{1}{2}^-$	0	1	1^-	2595.4 ± 0.6	$3.6^{+2.0}_{-1.3}$	$\Sigma_c\pi, \Lambda_c\pi\pi$
$\Lambda_c(2625)^+$	$\frac{3}{2}^-$	0	1	1^-	2628.1 ± 0.6	< 1.9	$\Lambda_c\pi\pi, \Sigma_c\pi$
$\Lambda_c(2765)^+$	$?^?$	?	?	?	2766.6 ± 2.4	50	$\Sigma_c\pi, \Lambda_c\pi\pi$
$\Lambda_c(2880)^+$	$\frac{5}{2}^+$	?	?	?	2881.5 ± 0.3	5.5 ± 0.6	$\Sigma_c^{(*)}\pi, \Lambda_c\pi\pi, D^0p$
$\Lambda_c(2940)^+$	$?^?$	?	?	?	2938.8 ± 1.1	13.0 ± 5.0	$\Sigma_c^{(*)}\pi, \Lambda_c\pi\pi, D^0p$
$\Sigma_c(2455)^{++}$	$\frac{1}{2}^+$	1	0	1^+	2454.02 ± 0.18	2.23 ± 0.30	$\Lambda_c\pi$
$\Sigma_c(2455)^+$	$\frac{1}{2}^+$	1	0	1^+	2452.9 ± 0.4	< 4.6	$\Lambda_c\pi$
$\Sigma_c(2455)^0$	$\frac{1}{2}^+$	1	0	1^+	2453.76 ± 0.18	2.2 ± 0.4	$\Lambda_c\pi$
$\Sigma_c(2520)^{++}$	$\frac{3}{2}^+$	1	0	1^+	2518.4 ± 0.6	14.9 ± 1.9	$\Lambda_c\pi$
$\Sigma_c(2520)^+$	$\frac{3}{2}^+$	1	0	1^+	2517.5 ± 2.3	< 17	$\Lambda_c\pi$
$\Sigma_c(2520)^0$	$\frac{3}{2}^+$	1	0	1^+	2518.0 ± 0.5	16.1 ± 2.1	$\Lambda_c\pi$
$\Sigma_c(2800)^{++}$	$\frac{3}{2}^-?$	1	1	2^-	2801^{+4}_{-6}	75^{+22}_{-17}	$\Lambda_c\pi, \Sigma_c^{(*)}\pi, \Lambda_c\pi\pi$
$\Sigma_c(2800)^+$	$\frac{3}{2}^-?$	1	1	2^-	2792^{+14}_{-5}	62^{+60}_{-40}	$\Lambda_c\pi, \Sigma_c^{(*)}\pi, \Lambda_c\pi\pi$
$\Sigma_c(2800)^0$	$\frac{3}{2}^-?$	1	1	2^-	2802^{+4}_{-7}	61^{+28}_{-18}	$\Lambda_c\pi, \Sigma_c^{(*)}\pi, \Lambda_c\pi\pi$
Ξ_c^+	$\frac{1}{2}^+$	0	0	0^+	2467.9 ± 0.4		weak
Ξ_c^0	$\frac{1}{2}^+$	0	0	0^+	2471.0 ± 0.4		weak
$\Xi_c'^+$	$\frac{1}{2}^+$	1	0	1^+	2575.7 ± 3.1		$\Xi_c\gamma$
$\Xi_c'^0$	$\frac{1}{2}^+$	1	0	1^+	2578.0 ± 2.9		$\Xi_c\gamma$
$\Xi_c(2645)^+$	$\frac{3}{2}^+$	1	0	1^+	2646.6 ± 1.4	< 3.1	$\Xi_c\pi$
$\Xi_c(2645)^0$	$\frac{3}{2}^+$	1	0	1^+	2646.1 ± 1.2	< 5.5	$\Xi_c\pi$
$\Xi_c(2790)^+$	$\frac{1}{2}^-$	0	1	1^-	2789.2 ± 3.2	< 15	$\Xi_c'\pi$
$\Xi_c(2790)^0$	$\frac{1}{2}^-$	0	1	1^-	2791.9 ± 3.3	< 12	$\Xi_c'\pi$
$\Xi_c(2815)^+$	$\frac{3}{2}^-$	0	1	1^-	2816.5 ± 1.2	< 3.5	$\Xi_c^*\pi, \Xi_c\pi\pi, \Xi_c'\pi$
$\Xi_c(2815)^0$	$\frac{3}{2}^-$	0	1	1^-	2818.2 ± 2.1	< 6.5	$\Xi_c^*\pi, \Xi_c\pi\pi, \Xi_c'\pi$
$\Xi_c(2980)^+$	$?^?$	?	?	?	2971.1 ± 1.7	25.2 ± 3.0	see Table 7 of [2]
$\Xi_c(2980)^0$	$?^?$	?	?	?	2977.1 ± 9.5	43.5	see Table 7 of [2]
$\Xi_c(3055)^+$	$?^?$	?	?	?	3054.2 ± 1.3	17 ± 13	$\Lambda_c^+\bar{K}^0$, $\Lambda_c^+K^-\pi^+$
$\Xi_c(3080)^+$	$?^?$	?	?	?	3076.5 ± 0.6	6.2 ± 1.1	see Table 7 of [2]
$\Xi_c(3080)^0$	$?^?$	?	?	?	3082.8 ± 2.3	5.2 ± 3.6	see Table 7 of [2]
$\Xi_c(3123)^+$	$?^?$	?	?	?	3122.9 ± 1.3	4.4 ± 3.8	$\Lambda_c^+\bar{K}^0$, $\Lambda_c^+K^-\pi^+$
Ω_c^0	$\frac{1}{2}^+$	1	0	1^+	2697.5 ± 2.6		weak
$\Omega_c(2770)^0$	$\frac{3}{2}^+$	1	0	1^+	2768.3 ± 3.0		$\Omega_c\gamma$

since according to the $^3P_0$ model [12]

$$\frac{\Gamma\left(\Lambda_{c2}(5/2^+) \to \Sigma_c^*\pi\right)}{\Gamma\left(\Lambda_{c2}(5/2^+) \to \Sigma_c\pi\right)} = 0.06\,,$$
$$\frac{\Gamma\left(\hat{\Lambda}_{c2}(5/2^+) \to \Sigma_c^*\pi\right)}{\Gamma\left(\hat{\Lambda}_{c2}(5/2^+) \to \Sigma_c\pi\right)} = 78.3\,. \quad (5)$$

Both symmetric states Λ_{c2} and $\hat{\Lambda}_{c2}$ are thus ruled out as the predicted ratio R is either too small or too big compared to experiment. However, the assignment of $\Lambda''_{c3}(\frac{5}{2}^+)$ for $\Lambda_c(2880)$ has an issue with the spectrum: The quark model indicates a $\Lambda_{c2}(\frac{5}{2}^+)$ state around 2910 MeV which is close to the mass of $\Lambda_c(2880)$, while the mass of $\Lambda''_{c3}(\frac{5}{2}^+)$ is higher [1].

It is interesting to notice that, based on the diquark idea, the quantum numbers $J^P = \frac{5}{2}^+$ have been correctly predicted in [13] for the $\Lambda_c(2880)$ before the Belle experiment.

The highest $\Lambda_c(2940)^+$ was first discovered by BaBar in the D^0p decay mode [10] and confirmed by

Belle in the decays $\Sigma_c^0\pi^+, \Sigma_c^{++}\pi^-$ which subsequently decay into $\Lambda_c^+\pi^+\pi^-$ [11]. Since the mass of $\Lambda_c(2940)^+$ is barely below the threshold of $D^{*0}p$, this observation has motivated the authors of [14] to suggest an exotic molecular state of D^{*0} and p with a binding energy of order 6 MeV and $J^P = \frac{1}{2}^-$ for $\Lambda_c(2940)^+$. The quark potential model predicts a $\frac{5}{2}^-$ Λ_c state at 2900 MeV and a $\frac{3}{2}^+$ Λ_c state at 2910 MeV [1]. A similar result of 2906 MeV for $\frac{3}{2}^+$ Λ_c is also obtained in the relativistic quark model [15]. Given the uncertainty of order 50 MeV for the quark model calculation, this suggests that the possible allowed J^P numbers of the highest $\Lambda_c(2940)^+$ are $\frac{5}{2}^-$ and $\frac{3}{2}^+$. Hence, the potential candidates are $\tilde{\Lambda}_{c2}(\frac{5}{2}^-)$, $\Lambda_{c2}(\frac{3}{2}^+)$, $\hat{\Lambda}_{c2}(\frac{3}{2}^+)$, $\tilde{\Lambda}'_{c1}(\frac{3}{2}^+)$, $\tilde{\Lambda}''_{c1}(\frac{3}{2}^+)$ and $\tilde{\Lambda}''_{c2}(\frac{3}{2}^+)$. Since the predicted ratios differ significantly for different J^P quantum numbers, the measurements of the ratio of $\Sigma_c^*\pi/\Sigma_c\pi$ will enable us to discriminate the J^P assignments for $\Lambda_c(2940)$ [2]. Note that it has been argued in [8] that $\Lambda_c(2940)$ is the first radial excitation of Σ_c (not Λ_c !) with $J^P = 3/2^+$.

2.2. Σ_c

The highest isotriplet charmed baryons $\Sigma_c(2800)^{++,+,0}$ decaying to $\Lambda_c^+\pi$ were first measured by Belle [16]. They are most likely to be the $J^P = \frac{3}{2}^-$ Σ_{c2} states because the $\Sigma_{c2}(\frac{3}{2}^-)$ baryon decays principally into the $\Lambda_c\pi$ system in a D-wave, while $\Sigma_{c1}(\frac{3}{2}^-)$ decays mainly to the two pion system $\Lambda_c\pi\pi$ in a P-wave. The state $\Sigma_{c0}(\frac{1}{2}^-)$ can decay into $\Lambda_c\pi$ in an S-wave, but it is very broad with width of order 406 MeV. Therefore, $\Sigma_c(2800)^{++,+,0}$ are likely to be $\Sigma_{c2}(\frac{3}{2}^-)$ with a possible small mixing with $\Sigma_{c0}(\frac{1}{2}^-)$.

2.3. Ξ_c

The states $\Xi_c(2790)$ and $\Xi_c(2815)$ form a doublet $\Xi_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$. Since the diquark transition $1^- \to 0^+ + \pi$ is prohibited, $\Xi_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$ cannot decay to $\Xi_c\pi$. The dominant decay mode is $[\Xi'_c\pi]_S$ for $\Xi_{c1}(\frac{1}{2}^-)$ and $[\Xi_c^*\pi]_S$ for $\Xi_{c1}(\frac{3}{2}^-)$ where Ξ_c^* stands for $\Xi_c(2645)$.

The new charmed strange baryons $\Xi_c(2980)^+$ and $\Xi_c(3080)^+$ that decay into $\Lambda_c^+K^-\pi^+$ were first observed by Belle [17] and confirmed by BaBar [18]. For the charmed states $\Xi_c(2980)$ and $\Xi_c(3080)$, they could be the first positive-parity excitations of Ξ_c in viewing of their large masses. Since the mass difference between the antitriplets Λ_c and Ξ_c for $J^P = \frac{1}{2}^+, \frac{1}{2}^-, \frac{3}{2}^-$ is of order $180 \sim 200$ MeV, it is conceivable that $\Xi_c(2980)$ and $\Xi_c(3080)$ are the counterparts of $\Lambda_c(2765)$ and $\Lambda_c(2880)$, respectively, in the strange charmed baryon sector. As noted in passing, the state $\Lambda_c(2765)^+$ could be an even-parity orbital excitation or a radial excitation and $\Lambda_c(2880)$ has the quantum numbers $J^P = \frac{5}{2}^+$, it is thus tempting to assign $J^P = 1\frac{1}{2}^+$ for $\Xi_c(2980)$ and $\frac{5}{2}^+$ for $\Xi_c(3080)$. The possible strong decays of the first positive-parity excitations of the Ξ_c states are summarized in Table VII of [2]. Since the two-body modes $\Xi_c\pi$, Λ_cK, $\Xi'_c\pi$ and Σ_cK are in P (F) waves and the three-body modes $\Xi_c\pi\pi$ and $\Lambda_cK\pi$ are in S (D) waves in the decays of $\frac{1}{2}^+$ ($\frac{5}{2}^+$), this explains why $\Xi_c(2980)$ is broader than $\Xi_c(3080)$. Since both $\Xi_c(2980)$ and $\Xi_c(3080)$ are above the $D\Lambda$ threshold, it is important to search for them in the $D\Lambda$ spectrum as well.

Two new Ξ_c resonances $\Xi_c(3055)$ and $\Xi_c(3123)$ were recently reported by BaBar [19] with masses and widths shown in Table II.

2.4. Ω_c

At last, the $J^P = \frac{3}{2}^+$ $\Omega_c(2770)$ charmed baryon was recently observed by BaBar in the decay $\Omega_c(2770)^0 \to \Omega_c^0\gamma$ [20]. With this new observation, the $\frac{3}{2}^+$ sextet is finally completed. However, it will be very difficult to measure the electromagnetic decay rate because the width of Ω_c^*, which is predicted to be of order 0.9 keV [21], is too narrow to be experimentally resolvable.

The possible spin-parity quantum numbers of the newly discovered charmed baryon resonances that have been suggested in the literature are summarized in Table III. Some of the predictions are already ruled out by experiment. For example, $\Lambda_c(2880)$ has $J^P = \frac{5}{2}^+$ as seen by Belle. Certainly, more experimental studies are needed in order to pin down the quantum numbers.

3. Strong decays

Due to the rich mass spectrum and the relatively narrow widths of the excited states, the charmed baryon system offers an excellent ground for testing the ideas and predictions of heavy quark symmetry and light flavor SU(3) symmetry. The pseudoscalar mesons involved in the strong decays of charmed baryons such as $\Sigma_c \to \Lambda_c\pi$ are soft. Therefore, heavy quark symmetry of the heavy quark and chiral symmetry of the light quarks will have interesting implications for the low-energy dynamics of heavy baryons interacting with the Goldstone bosons.

The strong decays of charmed baryons are most conveniently described by the heavy hadron chiral Lagrangians in which heavy quark symmetry and chiral symmetry are incorporated [22, 23]. The Lagrangian

Table III Possible spin-parity quantum numbers for the newly discovered charmed baryon resonances that have been proposed in the literature. First radial excited states are denoted by $2J^P$.

	$\Lambda_c(2765)$	$\Lambda_c(2880)$	$\Lambda_c(2940)$	$\Sigma_c(2800)$	$\Xi_c(2980)$	$\Xi_c(3080)$
Ebert et al. [8]	$2\frac{1}{2}^+, \frac{3}{2}^-(\Sigma_c)$	$\frac{5}{2}^+$	$2\frac{3}{2}^+(\Sigma_c)$	$\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$	$2\frac{1}{2}^+$	$\frac{5}{2}^+$
Garcilazo et al. [15]	$\frac{1}{2}^+$	$\frac{1}{2}^-, \frac{3}{2}^-$	$\frac{3}{2}^+$	$\frac{1}{2}^-, \frac{3}{2}^-$		
Gerasyuata et al. [9]	$\frac{5}{2}^-$	$\frac{1}{2}^-$		$\frac{5}{2}^-$		
Capstick et al. [1]	$\frac{1}{2}^+$		$\frac{3}{2}^+, \frac{5}{2}^-$			
Cheng et al. [2]					$\frac{1}{2}^+$	$\frac{5}{2}^+$
Wilczek et al. [13]		$\frac{5}{2}^+$				
He et al. [14]			$\frac{1}{2}^-$			

involves two coupling constants g_1 and g_2 for P-wave transitions between s-wave and s-wave baryons [22], six couplings $h_2 - h_7$ for the S-wave transitions between s-wave and p-wave baryons, and eight couplings $h_8 - h_{15}$ for the D-wave transitions between s-wave and p-wave baryons [24].

3.1. Strong decays of s-wave charmed baryons

In principle, the coupling g_1 can be determined from the decay $\Sigma_c^* \to \Sigma_c\pi$. Unfortunately, this strong decay is kinematically prohibited since the mass difference between Σ_c^* and Σ_c is only of order 65 MeV. Consequently, the coupling g_1 cannot be extracted directly from the strong decays of heavy baryons. As for the coupling g_2, one can use the measured rates of $\Sigma_c^{++} \to \Lambda_c^+\pi^+$, $\Sigma_c^{*++} \to \Lambda_c^+\pi^+$ and $\Sigma_c^{*0} \to \Lambda_c^+\pi^-$ as inputs to obtain

$$|g_2| = 0.605^{+0.039}_{-0.043}, \quad 0.57 \pm 0.04, \quad 0.60 \pm 0.04, \tag{6}$$

respectively, where we have neglected the tiny contributions from electromagnetic decays. Hence, the averaged g_2 is

$$|g_2| = 0.591 \pm 0.023. \tag{7}$$

Using this value of g_2, the predicted total width of Ξ_c^{*+} is found to be in the vicinity of the current limit $\Gamma(\Xi_c^{*+}) < 3.1$ MeV [25].

It is clear from Table IV that the strong decay width of Σ_c is smaller than that of Σ_c^* by a factor of ~ 7, although they will become the same in the limit of heavy quark symmetry. This is ascribed to the fact that the c.m. momentum of the pion is around 90 MeV in the decay $\Sigma_c \to \Lambda_c\pi$ while it is two times bigger in $\Sigma_c^* \to \Lambda_c\pi$. Since Σ_c states are significantly narrower than their spin-$\frac{3}{2}$ counterparts, this explains why the measurement of their widths came out much later.

Table IV Decay widths (in units of MeV) of s-wave charmed baryons.

Decay	Expt.	HHChPT
$\Sigma_c^{++} \to \Lambda_c^+\pi^+$	2.23 ± 0.30	input
$\Sigma_c^+ \to \Lambda_c^+\pi^0$	< 4.6	2.5 ± 0.2
$\Sigma_c^0 \to \Lambda_c^+\pi^-$	2.2 ± 0.4	input
$\Sigma_c(2520)^{++} \to \Lambda_c^+\pi^+$	14.9 ± 1.9	input
$\Sigma_c(2520)^+ \to \Lambda_c^+\pi^0$	< 17	16.6 ± 1.3
$\Sigma_c(2520)^0 \to \Lambda_c^+\pi^-$	16.1 ± 2.1	input
$\Xi_c(2645)^+ \to \Xi_c^{0,+}\pi^{+,0}$	< 3.1	2.7 ± 0.2
$\Xi_c(2645)^0 \to \Xi_c^{+,0}\pi^{-,0}$	< 5.5	2.8 ± 0.2

3.2. Strong decays of p-wave charmed baryons

Some of the S-wave and D-wave couplings of p-wave baryons to s-wave baryons can be determined. In principle, the coupling h_2 is readily extracted from $\Lambda_c(2595)^+ \to \Sigma_c^0\pi^+$ with $\Lambda_c(2595)$ being identified as $\Lambda_{c1}(\frac{1}{2}^-)$. However, since $\Lambda_c(2595)^+ \to \Sigma_c\pi$ is kinematically barely allowed, the finite width effects of the intermediate resonant states could become important [26]. Before proceeding to a more precise determination of h_2, we make several remarks on the partial widths of $\Lambda_c(2595)^+$ decays. (i) PDG [6] has assumed the isospin relation, namely, $\Gamma(\Lambda_c^+\pi^+\pi^-) = 2\Gamma(\Lambda_c^+\pi^0\pi^0)$ to extract the branching ratios for $\Sigma_c\pi$ modes. However, the decay $\Lambda_c(2595) \to \Lambda_c\pi\pi$ occurs very close to the threshold as $m_{\Lambda_c(2595)} - m_{\Lambda_c} = 308.9 \pm 0.6$ MeV. Hence, the phase space is very sensitive to the small isospin-violating mass differences between members of pions and charmed Sigma baryon multiplets. Since the neutral pion is slightly lighter than the charged one, it turns out that both $\Lambda_c^+\pi^+\pi^-$ and $\Lambda_c^+\pi^0\pi^0$ have very similar rates. (ii) Taking $\mathcal{B}(\Lambda_c(2595)^+ \to \Lambda_c^+\pi^+\pi^-) \approx 0.5$ and using the measured ratios of $\Lambda_c(2595)^+ \to \Sigma_c^{++}\pi^-)$ and $\Sigma_c^0\pi^+$ rela-

Table V Same as Table IV except for p-wave charmed baryons.

Decay	Expt.	HHChPT
$\Lambda_c(2595)^+ \to (\Lambda_c^+\pi\pi)_R$	$2.63^{+1.56}_{-1.09}$	input
$\Lambda_c(2595)^+ \to \Sigma_c^{++}\pi^-$	$0.65^{+0.41}_{-0.31}$	$0.72^{+0.43}_{-0.30}$
$\Lambda_c(2595)^+ \to \Sigma_c^{0}\pi^+$	$0.67^{+0.41}_{-0.31}$	$0.77^{+0.46}_{-0.32}$
$\Lambda_c(2595)^+ \to \Sigma_c^{+}\pi^0$		$1.57^{+0.93}_{-0.65}$
$\Lambda_c(2625)^+ \to \Sigma_c^{++}\pi^-$	< 0.10	≤ 0.029
$\Lambda_c(2625)^+ \to \Sigma_c^{0}\pi^+$	< 0.09	≤ 0.029
$\Lambda_c(2625)^+ \to \Sigma_c^{+}\pi^0$		≤ 0.041
$\Lambda_c(2625)^+ \to \Lambda_c^+\pi\pi$	< 1.9	≤ 0.21
$\Sigma_c(2800)^{++} \to \Lambda_c\pi, \Sigma_c^{(*)}\pi$	75^{+22}_{-17}	input
$\Sigma_c(2800)^{+} \to \Lambda_c\pi, \Sigma_c^{(*)}\pi$	62^{+60}_{-40}	input
$\Sigma_c(2800)^{0} \to \Lambda_c\pi, \Sigma_c^{(*)}\pi$	61^{+28}_{-18}	input
$\Xi_c(2790)^+ \to \Xi_c'^{0,+}\pi^{+,0}$	< 15	$8.0^{+4.7}_{-3.3}$
$\Xi_c(2790)^0 \to \Xi_c'^{+,0}\pi^{-,0}$	< 12	$8.5^{+5.0}_{-3.5}$
$\Xi_c(2815)^+ \to \Xi_c^{*+,0}\pi^{0,+}$	< 3.5	$3.4^{+2.0}_{-1.4}$
$\Xi_c(2815)^0 \to \Xi_c^{*+,0}\pi^{-,0}$	< 6.5	$3.6^{+2.1}_{-1.5}$

tive to $\Lambda_c(2595)^+ \to \Lambda_c^+\pi^+\pi^-$), we obtain

$$\begin{aligned}\Gamma(\Lambda_c(2595)^+ \to \Sigma_c^{++}\pi^-) &= 0.65^{+0.41}_{-0.31}\,\mathrm{MeV},\\ \Gamma(\Lambda_c(2595)^+ \to \Sigma_c^{0}\pi^+) &= 0.67^{+0.41}_{-0.31}\,\mathrm{MeV}. \quad (8)\end{aligned}$$

(iii) The non-resonant or direct three-body decay mode $\Lambda_c^+\pi^+\pi^-$ has a branching ratio of 0.14 ± 0.08 [6]. Assuming the same for $\Lambda_c^+\pi^0\pi^0$ and using the measured total width of $\Lambda_c(2595)^+$, we are led to

$$\begin{aligned}\Gamma(\Lambda_c(2595)^+ \to \Lambda_c^+\pi\pi)_{\rm R} &= (2.63^{+1.56}_{-1.09})\,\mathrm{MeV},\\ \Gamma(\Lambda_c(2595)^+ \to \Lambda_c^+\pi\pi)_{\rm NR} &= (0.97^{+0.76}_{-0.64})\,\mathrm{MeV}. \quad (9)\end{aligned}$$

Consider the pole contributions to the decays $\Lambda_c(2595)^+, \Lambda_c(2625)^+ \to \Lambda_c^+\pi\pi$ with the finite width effects included. The intermediate states of interest are Σ_c and Σ_c^* poles. The decay rates depend on two coupling constants h_2 and h_8. Identifying the calculated $\Gamma(\Lambda_c(2595)^+ \to \Lambda_c^+\pi\pi)$ with the resonant one, we find

$$|h_2| = 0.437^{+0.114}_{-0.102}, \quad |h_8| < 3.65\times 10^{-3}\,\mathrm{MeV}^{-1}. \quad (10)$$

Assuming that the total width of $\Lambda_c(2593)^+$ is saturated by the resonant $\Lambda_c^+\pi\pi$ 3-body decays, Pirjol and Yan obtained $|h_2| = 0.572^{+0.322}_{-0.197}$ and $|h_8| \leq (3.50 - 3.68)\times 10^{-3}\,\mathrm{MeV}^{-1}$ [24]. Our value of h_2 is slightly smaller since in our case, the Σ_c and Σ_c^* poles only describe the *resonant* contributions to the total width of $\Lambda_c(2593)$.

The $\Xi_c(2790)$ and $\Xi_c(2815)$ baryons form a doublet $\Xi_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$. $\Xi_c(2790)$ decays to $\Xi_c'\pi$, while $\Xi_c(2815)$ decays to $\Xi_c\pi\pi$, resonating through Ξ_c^*, i.e. $\Xi_c(2645)$. Using the coupling h_2 obtained from (10) and the experimental observation that the $\Xi_c\pi\pi$ mode in $\Xi_c(2815)$ decays is consistent with being entirely via $\Xi_c^*\pi$ [27], the predicted $\Xi_c(2790)$ and $\Xi_c(2815)$ widths are shown in Table V. The predictions are consistent with the current experimental limits.

Some information on the coupling h_{10} can be inferred from the strong decays of $\Sigma_c(2800)$. Assuming the widths of the states $\Sigma_c(2800)^{++,+,0}$ are dominated by the two-body D-wave modes $\Lambda_c\pi$, $\Sigma_c\pi$ and $\Sigma_c^*\pi$, and applying the quark model relation $|h_8| = |h_{10}|$ [24], we then have

$$|h_8| \leq (0.86^{+0.08}_{-0.10})\times 10^{-3}\,\mathrm{MeV}^{-1}, \quad (11)$$

which improves the previous limit (10) by a factor of 4.

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References

[1] S. Capstick and N. Isgur, Phys. Rev.D **34**, 2809 (1986); L.A. Copley, N. Isgur, and G. Karl, Phys. Rev. D **20**, 768 (1979).
[2] H.Y. Cheng and C.K. Chua, Phys. Rev. D **75**, 014006 (2007).
[3] R. Mizuk, talk presented at the XXIII International Symposium on Lepton and Photon Interactions at High Energy, August 13-18, 2007, Daegu, Korea.
[4] P. Cho, Phys. Rev. D **50**, 3295 (1994).
[5] CLEO collaboration, M. Artuso *et al.,* Phys. Rev. Lett. **86**, 4479 (2001).
[6] Particle Data Group, Y.M. Yao *et al.,* J. Phys. G **33**, 1 (2006).
[7] Y. Oh and B.Y. Park, Phys. Rev. D **53**, 1605 (1996).
[8] D. Ebert, R.N. Faustov, and V.O. Galkin, arXiv:0705.2957 [hep-ph].
[9] S.M. Gerasyuta and E.E. Matskevich, arXiv:0709.0397 [hep-ph].
[10] BaBar Collaboration, B. Aubert *et al.,* Phys. Rev. Lett. **98**, 012001 (2007).
[11] Belle Collaboration, K. Abe *et al.,* Phys. Rev. Lett. **98**, 262001 (2007).
[12] C. Chen, X.L. Chen, X. Liu, W.Z. Deng, and S.L. Zhu, Phys. Rev. D **75**, 094017 (2007).
[13] A. Selem, *A Diquark Interpretation of the Structure and Energies of Hadrons*, Senior thesis, M.I.T. (2005); A. Selem and F. Wilczek, hep-ph/0602128.

[14] X.G. He, X.Q. Li, X. Liu, and X.Q. Zeng, Eur. Phys. J. C **51**, 883 (2007).
[15] H. Garcilazo, J. Vijande, and A. Valcarce, J. Phys. G **34**, 961 (2007).
[16] Belle Collaboration, R. Mizuk *et al.,* Phys. Rev. Lett. **94**, 122002 (2005).
[17] Belle Collaboration, R. Chistov *et al.,* Phys. Rev. Lett. **97**, 162001 (2006).
[18] BaBar Collaboration, B. Aubert *et al.,* hep-ex/0607042
[19] T. Schröder, talk presented at International Europhysics Conference on High Energy Physics, Manchester, England, July 19-25, 2007.
[20] BaBar Collaboration, B. Aubert *et al.,* Phys. Rev. Lett. **97**, 232001 (2006).
[21] H.Y. Cheng, C.Y. Cheung, G.L. Lin, Y.C. Lin, T.M. Yan, and H.L. Yu Phys. Rev. D **49**, 5857 (1994); ibid, D **47**, 1030 (1993).
[22] T.M. Yan, H.Y. Cheng, C.Y. Cheung, G.L. Lin, Y.C. Lin, and H.L. Yu, Phys. Rev. D **46**, 1148 (1992); *ibid.* D **55**, 5851(E) (1997).
[23] M.B. Wise, Phys. Rev. D **45**, 2188 (1992); G. Burdman and J. Donoghue, Phys. Lett. B **280**, 287 (1992).
[24] D. Pirjol and T.M. Yan, Phys. Rev. D **56**, 5483 (1997).
[25] CLEO Collaboration, P. Avery *et al.,* Phys. Rev. Lett. **75**, 4364 (1995); L. Gibbons *et al., ibid.* **77**, 810 (1996).
[26] A.E. Blechman, A.F. Falk, D. Pirjol, and J.M. Yelton, Phys. Rev. D **67**, 074033 (2003).
[27] CLEO Collaboration, J.P. Alexander *et al.,* Phys. Rev. Lett. **83**, 3390 (1999).